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Original Article

ENHANCEMENT OF STATIC FREQUENCY CONVERTER START-UP RELIABILITY FOR PUMPED STORAGE POWER UNITS OF GUANGZHOU PUMPED STORAGE POWER STATION

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ABSTRACT

With the quick development of the power grid in Guangdong Province, pumped storage power stations have been developing in large capacity form of grid energy storage in Guangdong Power Grid for meeting the high electricity demand under the rapid economic growth. Since the pumped storage power stations act as peaking plants and provide emergency response to maintain as afe and reliable power supply in the network systems, the reliability of pumps and generators start-up becomes critical to network operations. The 4 x 300MW pumped storage units of the Guangzhou Pumped Storage Power Station – Phase I [1] (GPSPS 'A' Station) were commissioned in 1990s and the success rate of unit start-up was 97%, comparing to the 99% achieved by the Guangzhou Pumped Storage Power Station – Phase II (GPSPS 'B' Station) commissioned in 2000s.

This article describes the development process for enhancing the operation reliability of GPSPS including strategy formulation, field trial (iteration), and continuous improvement on the detection of initial rotor position methods for static frequency converter (SFC) start-up.

The improvement process mainly comprises two stages of implementation (first stage in 2005-2007, second stage in July 2010) followed by a performance evaluation period (from 2011 to 2015). The operation records indicated that the success rate of rotor position detection has been improved to100%. The overall motor start-up reliability has been improved from 97% to 99%.

KEYWORDS: Static Frequency Convertor; Rotor Initial Position; Variable Frequency Start-Up & Pumped Storage Power Station

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INTRODUCTION

Background

The pumped storage power stations are mainly used as peaking plants and provide emergency response to sustain safe and reliable power supply in the network systems. Therefore, the reliability of either starting the units as pumps or generators becomes critical to network operations. The 4 x 300MW pumped storage units of the

GPSPS ‘A’ Station were commissioned in 1990s and the success rate of startups was 97% in early stage, which was below the 99% achieved by GPSPS ‘B’ Station. This article describes the development process for enhancing the operation reliability of GPSPS including strategy formulation, field trial (iteration), and continuous improvement on the detection of initial rotor position methods for static frequency converter (SFC) start-up.

Introduction

The Southern Power Grid Company Limited (CSG) is one of the two state-owned power grid enterprises established in 2002 by the State Council of the People's Republic of China (PRC). It takes charges of investment, construction and management of power transmission and distribution network in five southern provinces of PRC including Guangdong, Guangxi, Yunnan, Guizhou and Hainan.

The Power Generation Company (PGC) is one of the branch of CSG that in charge of operation, maintenance, management and construction of power plants in the service areas of CSG. At present, PGC owns and operates Tian-sheng-qiao Hydro Power Plant, Lubuge Hydro Power Plant, Guangzhou Pumped Storage and Huizhou Pumped Storage Power Plants located in Guizhou, Yunnan and Guangdong.

GPSPS is located in Lvtian, Conghua district, 120km north-east of Guangzhou, capital of Guangdong Province. The GPSPS was constructed in two stages with total installed capacity of 2,400MW. Hong Kong Pumped Storage Development Company Limited (PSDC) is a wholly-owned subsidiary of CLP Power Hong Kong Limited (CLP), which has contractual rights to use 600MW of the first stage (GPSPS ‘A’ Station) i.e. equivalent to half of its installed capacity.

CLP participated in the development of the GPSPS ‘A’ Station through PSDC and uses the contracted pumped storage capacity for supporting the operation and security of the Hong Kong electricity supply system. The average unplanned customer minutes lost per year was 1.5 minutes (2013-2015 average for CLP Power Hong Kong).

Pump Start-Up Principle and its Challenges

Static frequency converter (SFC) means that there are no rotary parts inside it - also called solid state - the definition is relative to rotary frequency converter which is using an electric motor to output adjustable frequency. It is changing fixed grid power through AC to DC to AC by inner electronic parts and components, the multifunctional inverter converts the mains through conversion circuit and transforms into the required voltage and frequency power source [2]. SFC provides the flexibility needed to adjust the electromagnetic torque developed by the machine to the load torque, allowing “soft-starting” of the pumped storage units. The resulting benefits are that the starting current is limited to the rated current or less that in turn minimizes the starting impact on the network and machine, and the control of acceleration of the water turbine rotor from standstill to the self-sustaining speed is achievable.

The basic machine start-up principle of the GPSPS ‘A’ Station is as follows:

To start up a pumped storage unit as a pump, an excitation current is applied to the rotor to create a transient electromagnetic flux that in turn induced an electromagnetic force ($emf=di/dt$ or $emf=d\Phi/dt$) in the stator windings. The potential difference at the terminals of the stator windings and the induced voltage of the stator flux are measured to identify the last rotor stop position and then triggers the most suitable pair of crystal tubes for providing maximum starting torque. The SFC starts the pumped unit from zero to it srated speed by injecting a variable frequency current, which changes with rotor speed, to the stator windings.

Table 1: Generator Parameters

1	Rating	333 MVA
2	Power factor	0.9
3	Frequency	50 Hz
4	Rated Voltage	18 kV
5	Rated Current	10,692 A
6	Rotation	500 rpm

Stator

Rotor

Figure 1

FIRST STAGE IMPROVEMENT OF THE STATIC FREQUENCY CONVERTER START-UP

(can this be deleted as it was very repetitive?)

The original design of the SFC start-up system and the rotor initial position detection of GPSPS ‘A’ Station makes use of a series of electro-mechanical relays to perform control logic. The key process sequences are highlighted as follows:

- Operator pushes the startup button to execute pumping start up sequence.
- The Remote Terminal Unit (RTU) received the startup command then process Static Frequency Converter (SFC) sequence.
- Static Frequency Converter (SFC) sends the command "EXCITATION 1ST REFERENCE" to trigger Relay K10 to start the measuring rotor position detection.
- The closing coil of Relay K1 is triggered to input excitation direct current at 600A to rotor.
- At the same time, the command send to Relay K14 to start the rotor position detection sequence.
- Relay K14to trigger the SFC PIB101C then start SFC program which delay 80ms time window open after the detection of the rotor position.
- Based on the time exit from the stator voltage transformer’ and obtaining three-phase transient EMF, the initial position of the rotor can be calculated.

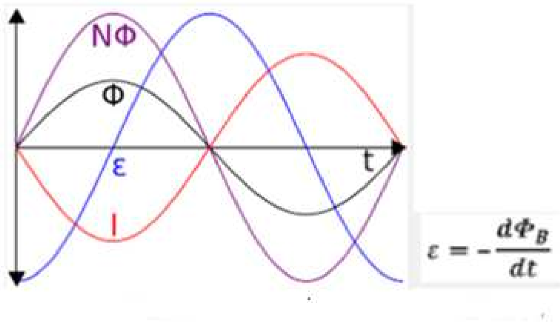

Figure 2: Induced Electroimagntic Force

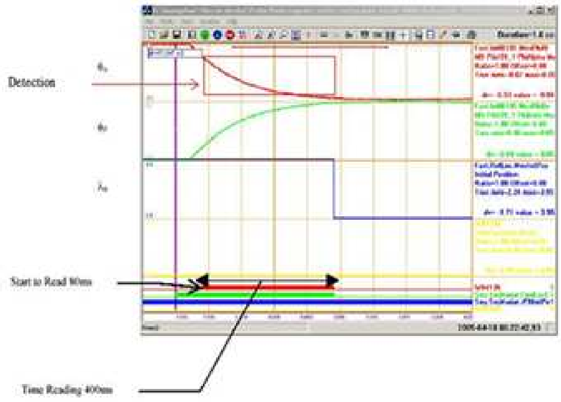

Figure 3: SFC Measuring Rotor Initial Position in the Oscillography

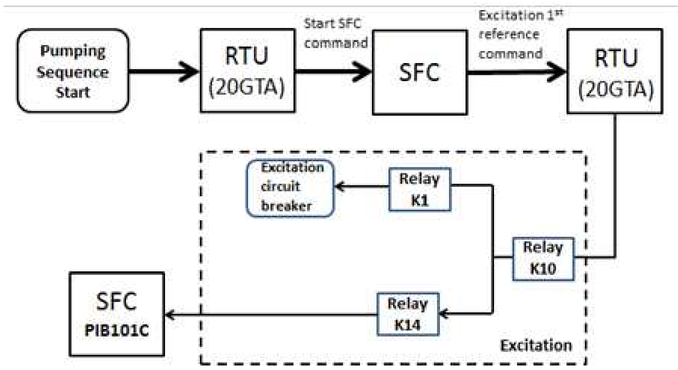

Figure 4: SFC Measuring Rotor Initial Position process

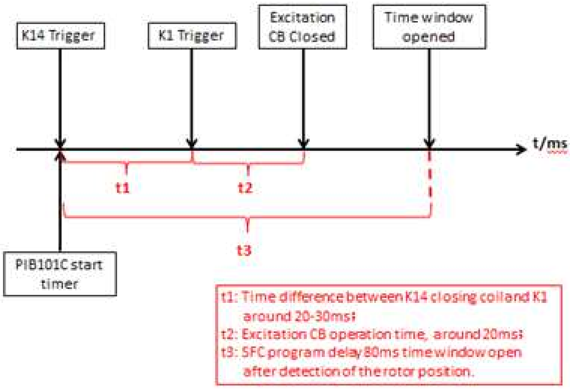

Figure 5: SFC Measuring Rotor Initial Position time interval

One of the critical success factors for successful startup is the time delay between two switches i.e. the SFC in the excitations witch closing and the detection of the rotor position that has to be controlled within 20~30ms after the first excitation current is injected to the rotor.

With reference to the above processes, it is obvious that the detection of the initial rotor position for SFC start relies heavily on the external circuits which include the public RTU commands, looping excitation switches (electro-mechanical relays) such as the K10, K14 relays of the excitation system. Such arrangement has put the SFC startup process in a very vulnerable position because failure on any one of these circuits or components would lead to error in detecting the initial position of the rotor, causing unit failed to start. Particular attention shall be put on the time excitation system in which the timer relay K14 has a string entrequirements of advanced switching of 10 ~ 30ms exciting action. In case that the relay settings or exciter switch K1 closing time drift, the detection of the initial position of the rotor in the SFC start-up process would fail. Furthermore, the relay K14 is required to be operated all the time during the unit operation that would cause prolonged heating of the internal electronic components and frequent drift of relay settings. In accordance with the operation records, among all the components involved in the SFC startup process, the relay K14 had the comparatively higher failure rate.. Therefore, the performance of the electromagnetic relays is vital to the whole start-up process and determines the success of unit startup [3].

For easy of explanation of analysis, let's assume that there is only one pair of pole, the electrical angle is in line with the spatial angle, and the bridge is a three-phase full-controlled bridge.

The initial position of the rotor may be at any angle from 0° to 359°, however, there are only six possible combinations for the conduction of bridge arm. Therefore, in order to cope with the bridge control requirements, the internal area of the stator is sub-divided into six equal sectors each covers a spatial area of 60° and the initial position of the rotor must fall into one of these six sectors.

It is not possible to determine the position of the rotor when it is standstill since there is no relative movement between the stator and the rotor and hence no change in electric flux. The initial position of a standstill rotor can be determined only at the time when an excitation current is applied which induces an electromotive force in the stator winding, by measurement of the induced electromotive forces so that the rotor position could be identified.

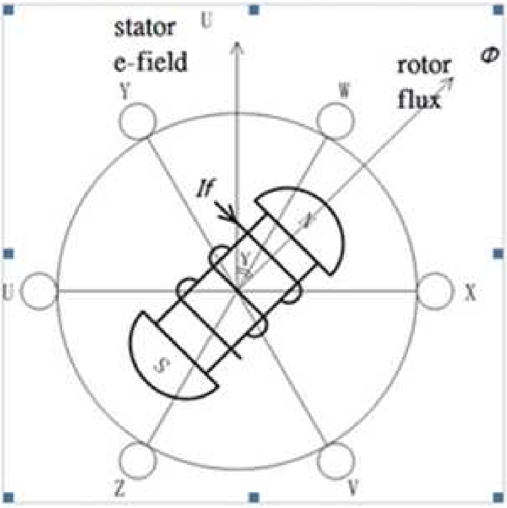

Figure 6: The Initial Position of the Rotor Synchronous Motors and Six Sectors

$$\begin{aligned} \Phi_u &= M i_f \cos(\gamma) \\ \Phi_v &= M i_f \cos(\gamma - 120°) \\ \Phi_w &= M i_f \cos(\gamma + 120°) \end{aligned} \tag{1}$$

Where:

- **Φ_u, Φ_v, Φ_w** are the flux induced in each of the three phases of the stator by the rotor current;
- M is the mutual inductance of the stator and rotor windings;
- $i_f$is the rotor current;
- γ is the angle between the axis of the rotor and the axis of the stator magnetic field of the U-phase.

By solving the above equations, the initial position of the rotor angle can be represented as follows:

$$\gamma = \tan^{-1}\left(\frac{u_{w0} - u_{v0}}{u_{u0}}\right) \tag{2}$$

Where **u_{w0}, u_{v0}, u_{u0}** are the induced voltages of each of the stator. These voltages are measured precisely by the voltage terminal unit. By collecting the voltage signal and using the formula (1) & (2) above, the angle γ could be calculated and hence the initial position of the rotor could be determined.

If there is a deviation in the detection of the rotor initial position, it may result in deviation in the determination of the actual rotor position. As a result, there would be insufficient torque for the rotor acceleration and the start-up would failure eventually. In theory, when the initial position of the rotor is at 60° i.e. at the boundary between sectors, it is likely that the rotor position cannot be identified correctly especially when the excitation flux is weak.

A number of field trials were conducted to measure the relationship between the magnitude of the percentage of magnetic flux (calculated value) in the stator with the success rate of static frequency converter start-up. The test results are as follows:

Table 2

	Success (√) or Failure (x)	Percentage of the magnetic flux in the stator in (%) (calculated value)		Success (√) or Failure (x)	Percentage of the magnetic flux in the stator in (%) (calculated value)
1	√	3.0	16	√	3.0
2	√	3.1	17	√	3.0
3	√	3.0	18	√	3.1
4	x	4.4	19	√	3.0
5	√	2.9	20	√	3.1
6	√	3.0	21	√	3.0
7	√	3.0	22	√	3.0
8	√	2.9	23	√	2.9
9	√	3.0	24	√	3.0
10	√	3.1	25	√	2.9
11	√	3.0	26	√	3.0
12	√	3.0	27	√	3.2
13	x	5.7	28	√	3.0
14	√	3.1	29	√	3.0
15	√	3.0	30	√	3.0

The test results above indicated that whenever the stator magnetic flux reaches or is closed to 3% of the rated flux (calculated value), the sensors of the SFC pick up the most accurate signal from the magnetic flux of the rotor. Instead of measurement of the rotor position after the first excitation current applied for 20~30ms, it can measure the stator magnetic flux for trigger the SFC start-up when it reaches or is closed to 3% (calculated value)The merit of this method is that it can greatly improve the success rate of SFC start-up with only minor modification on the existing control circuits, and the safety factor of the machine operation can be maintained as before or even higher without jeopardizing the safety operation of the power plant. The method also provides a convenient and reliable means of measuring the initial position of the rotor with the static frequency converter start-up. Since the implementation of first stage improvement work in July 2007, GPSPS 'A' Station unit startup in pumping mode has never come across a failure that is related to detection of rotor initial position, which is a significant achievement of GPSPS.

SECOND STAGE IMPROVEMENT OF THE SFC PUMP START-UP PROCESS

After the successful implementation of the first stage of improvement, the success rate of startups could be improved to 98%, however, there was still 2% failure rate caused by "Motor Stalled Failure" alarm. This alarm would be occurred under the following two situations:

- When the SFC detects the current of the bridge is more than 40% of the rated current while the rotor speed cannot reach 1.2% of rated speed, a "Motor Stalled Failure" alarm would be issued to trip SFC process after three seconds delay.
- When the SFC successfully detects the initial rotor position, it will send three pulse signals to trigger the thyristors. At this moment, if rotor rotational speed cannot reached10% of rated speed or higher the startup process would be also tripped.

Either of the above situations indicated that the rotor running speed is under the preset range or the rotor position could not be identified properly.

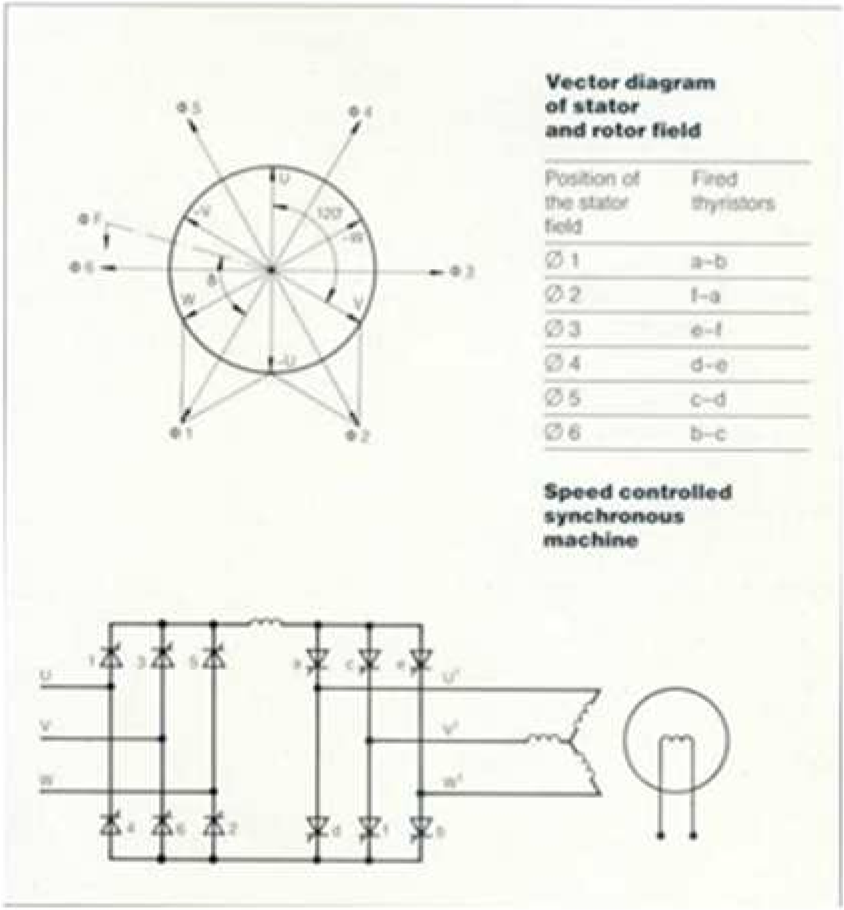

Figure 7: SCR Group Generator Connection Diagram and Electromagnetic Starting Torque Generated Schematics

Figure 6 illustrates an example when the starting torque of the electromagnetic size: $M = \Phi 1\ \Phi F \sin\delta$. Formula $\Phi 1$&ΦF are quantitative and M depends on the variable δ. When the angle of δ is small, the electromagnetic starting torque will be small too. As a result, unit was failed to start either because the rotor cannot be rotated or it is unable to reach the pre-requisite speed. According to generator stator generating arm, the induced magnetic flux can be divided into $\Phi 1$-$\Phi 6$, and their strength depend on the thyristor output current, the program is set to 40% of rated current and the angle difference is 60°. ΦF represents the flux generated by the excitation current in the rotor and its strength depends on a reference value of the current field. The size of the angle δ is random and it is determined by the final stop position of the rotor.

The success rate of start-up can be increased by providing sufficient magnetic moment M. An increased torque can help the machine reaching the pre-requisite speed. In accordance with the formula, $\Phi 1$ is not adjustable and $\delta$is random, adjust the excitation current to a reference value ΦF is the only controllable factor. Therefore, increasing the value of ΦF can increase the electromagnetic torque M.

During the period from April 2010 to January 2011, a technical upgrade was carried out on the four units of GPSPS ‘A’ Station and a series of field tests were conducted in order to determine the optimized reference excitation current and the results are as follows:

Table 3: The Field Test of the Excitation Current

Test	Excitation current(A)	Failure times in two months
1	600	Note: Design setting
2	630	2
3	650	3
4	680	2
5	700	1
6	730	1
7	750	0
8	>750	Note: System does not allowed excitation current over 750A; otherwise overcurrent alarm will be initiated.

The test results shown in table 3 indicated that the optimized excitation current is 750A. As such, the excitation current of the four units was adjusted from the original OEM designed value 600A to 750A for increasing the electromagnetic torque and therefore the success rate for unit startup in pumping mode.

It is noted that excitation current could not allowed to exceed 750A, otherwise, it will cause an over current alarm and the SFC start-up process will be stopped.

THE OVERALL EFFECT AFTER THE IMPLEMENTATION OF TWO OPTIMIZATION METHODS

In accordance with the operation records for the period from May 2005 to July 2007, GPSPS ‘A’ Station units had an annual average of 13 start-up failures related to failure indetection of the rotor position by SFC. Upon completion of the two stages of improvement work in 2010, the operation records over the past five years (from 2011 to 2015) indicated that the afore-mentioned annual average start-up failure has been greatly reduced to 2.5.

CONCLUSIONS

This paper describes how Guangzhou Pumped Storage Power Station ‘A’ Station taking an initiative for a continuous improvement process, enhancing the detection method of the initial rotor position for static frequency converter start-up for the 4 x 300MW pumped storage units in the last 10 years. It is concluded that applying 3% of the magnetic flux (calculated value) as a triggering signal and increasing the rotor field excitation current from 600A to 750A are two proven methods for increasing the success rate of SFC start-up process. The startup success rate for GPSPS ‘A’ Station has been improved from 97% to 99% after the implementation of the aforementioned two methods. The enhancement work improved the pump start-up reliability thus improving the electricity supply reliability. The new method is just small modifications to existing control circuit and the safety factor is still maintaining high, which is worth promoting applied in practice.

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